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Interactions exist in various ecological processes as well. Physical, chemical, and biological activities of plants and animals are affected directly by global climate change and by increased ultraviolet radiation resulting from depletion of stratospheric ozone.

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SCIENTIFIC LINKAGES IN GLOBAL CHANGE

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INTRODUCTION

The activities of man have long had local effects on the atmosphere. Now such effects have grown from local to regional and global proportion. In the last decade, scientists, policy makers, and the general public have focused increasing concern on two issues: ozone depletion in the upper atmosphere and global climate change. These two problems are not only global in scale, but are closely interrelated. Their primary linkages are in the areas of atmospheric processes and ecological processes. A sensitivity to the implications of these linkages may help society better plan to cope with each problem.

In the atmosphere, certain trace gases both promote global warming and deplete the ozone layer. The primary radiatively active trace gases, those that affect global warming, are carbon dioxide, nitrous oxide, chlorofluorocarbons, methane, and tropospheric ozone. In the troposphere, the atmosphere up to 10 miles above the earth's surface, these compounds function as greenhouse gases. Many of these gases also influence the concentration of ozone in the stratosphere, the atmospheric layer located between 10-30 miles above the earth's surface. This diffuse layer of ozone in the stratosphere protects life on earth from harmful solar radiation. A reduction of this layer could have very important impacts on the earth's systems.

Interactions exist in various ecological processes as well. Physical, chemical, and biological activities of plants and animals are affected directly by global climate change and by increased ultraviolet radiation resulting from depletion of stratospheric ozone.

The purposes of this paper are to both provide general background on the stratospheric ozone depletion issue, and to discuss the linkages surrounding both atmospheric and ecological processes.

BACKGROUND

The natural distribution of ozone in the earth's atmosphere is not uniform. It is concentrated primarily in a thin layer in the stratosphere where it blocks most of the ultraviolet radiation in the 290 to 320 nm range from reaching the earth's surface. This is known as the ultraviolet-B, or UV-B range. It can be damaging to humans, biological organisms, and man-made materials.

Many gases emitted as a result of man's industrial and agricultural activities can accumulate in the earth's atmosphere and ultimately contribute to alterations in the concentration and distribution of stratospheric ozone. These gases accumulate in the troposphere and then gradually migrate upward into the

stratosphere where they contribute to depletion of stratospheric ozone. The atmospheric and chemical processes involved in the destruction of ozone are extremely complex and are reviewed elsewhere [e.g., 1], but the following section will summarize one the most important interactions.

In recent years, the release into the atmosphere of halogens containing chlorine and bromine, compounds such as chlorofluorocarbons (CFCs) and halons, has resulted in the destruction of the protective ozone layer in the stratosphere. Short wavelength radiation hitting the stratosphere causes a breakup of the chlorofluorocarbons releasing the chlorine radicals (see figure 1). A chlorine radical destroys stratospheric ozone through a catalytic cycle producing oxygen molecules. After converting ozone to oxygen, the radical--now chlorine oxide--then reacts with an oxygen atom from another ozone molecule and emerges unchanged, ready to destroy more ozone.

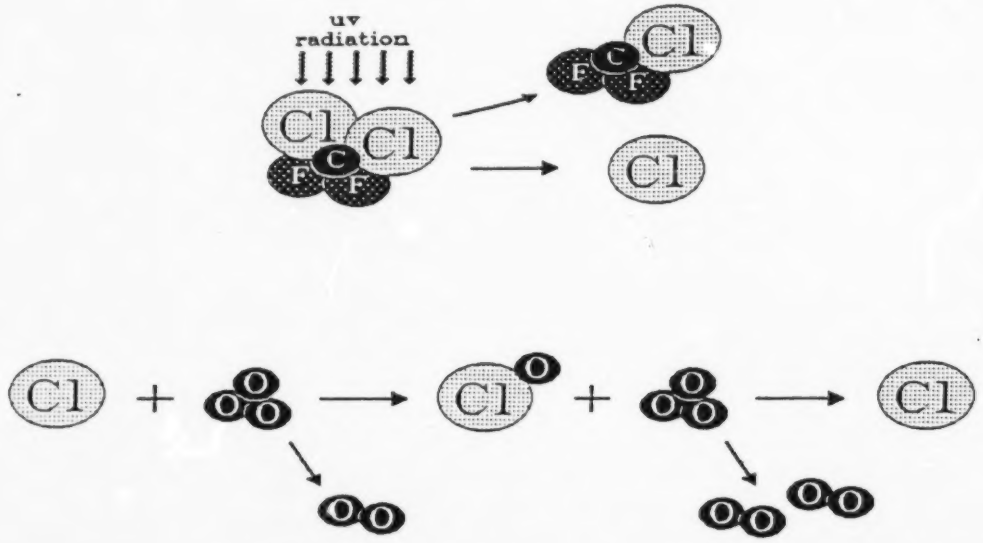

FIGURE 1. The catalytic cycle of a chlorine radical breaking down ozone into oxygen molecules.

Less ozone in the stratosphere will result in a greater transmission of ultraviolet radiation to the surface of the earth. Because of the long atmospheric lifetimes of CFCs and halons, scientists expect stratospheric ozone to continue to decrease into the middle of the next century even if emissions are curtailed worldwide [2].

Table 1 provides a summary of the major trace gases that contribute to ozone depletion, including their primary uses, atmospheric lifetime, and projected annual increase. Currently, the primary focus of regulations and mitigation options are on CFCs and halons, through the vehicle of the Montreal Protocol [3]. The treaty document was officially ratified in December 1988; regulatory provisions become effective in July 1989. The agreement calls for a freeze of CFC production (at 1986 levels) by 1989, a 20 percent decrease in production by 1993, and an additional 30 percent decrease by 1998.

Several recent national and international work group reports detailed discussions of the growing concern about stratospheric ozone depletion and assessment of scientific bases underlying such concern [e.g., 1, 4, 5]. A report by the Ozone Trends Panel has also highlighted the issue of stratospheric ozone depletion [6]. The panel's report describes the global decrease in stratospheric ozone in recent years and the probable role of CFCs and other ozone-depleting compounds in the development of the Antarctic ozone hole.

ATMOSPHERIC INTERACTIONS

Many of the atmospheric trace gases, such as chlorofluorocarbons, are relatively transparent in the visible region of the solar spectrum. They do, however, absorb the long wavelength radiation that is radiated back from the surface of the earth, resulting in what has come to be known as the greenhouse effect. In addition to CFCs, other gases contribute to the greenhouse effect, including carbon dioxide, methane, nitrous oxide, and tropospheric ozone. The effects of these gases on global warming is cumulative because each blocks different wavelength radiation. Their concentrations have been increasing over time, some more dramatically than others. This point is particularly important because of their relatively long atmospheric lifetimes, especially CFCs, halons and nitrous oxide.

Chlorofluorocarbons (CFCs).

The release of CFCs and other chlorine-containing compounds decreased initially in the 1970s as a result of regulatory action to ban selected, non-essential CFC compounds used as aerosol propellants. This regulation was enacted in several countries, including the United States. Currently, CFC production and consumption are increasing due at least in part to the involvement of newly industrialized and lesser developed countries in CFC use.

TABLE I. Trace gases affecting ozone concentrations and global climate change.

Trace Gas (Formula)	Primary Source	Ave. Life in Atmos.	ODP*	GP**
CFC-11 ($CFCl_3$)	Refrigerant/AC, Plastic Foams, Aerosols	75 yrs	1.0	0.40
CFC-12 (CF_2Cl_3)	Refrigerant/AC, Plastic Foams, Sterilants	110	1.0	1.00
CFC-113 ($C_2F_3Cl_3$)	Solvents	90	0.8	0.3-0.8
Halon 1211 (CF_2ClBr)	Fire Extinguisher	25	3.0	?
Halon 1301 (CF_3Br)	Fire Extinguisher	110	10.0	0.80
Carbon Tetrachloride (CCl_4)	Industrial Processes	67	1.1	0.05
Methyl Chloroform (CH_3CCl_3)	Industrial and Natural Processes	8	0.1	0.01
Nitrous Oxide (N_2O)	Fossil Fuels	150	--	0.016
Methane (CH_4)	Biogenic Activity, Fossil Fuels	11	--	0.001
Carbon Dioxide (CO_2)	Fossil Fuels	7	--	0.00005
Carbon Monoxide (CO)	Motor Vehicles, Biogenic Activity	0.4	--	--

* ozone depletion potential (CFC-11 = 1.0)

** greenhouse potential (CFC-12 = 1.0)

In addition to breaking down ozone through the action of chlorine radicals, chlorofluorocarbons contribute to the greenhouse effect. Estimates put the CFC contribution to global temperature change at 20-25 percent, although as a result of the Montreal Protocol it would be reduced to 15-20 percent.

Nitrous Oxide (N_2O).

Nitrous oxide in the atmosphere originates from both natural and man-made sources, including many bacterial processes involved in the nitrification or denitrification cycles. Recently, nitrous oxide has been increasing at a rate of about 0.2% annually. In the atmosphere N_2O is partly converted into nitrogen oxides (NO_x).

Nitrous oxide (N_2O) plays a role in both ozone depletion and global climate change. The N_2O functions as a greenhouse gas contributing to global warming. Converted to nitrogen oxides (NO_x) it destroys stratospheric ozone in a catalytic cycle similar to that of chlorine radicals. On the other hand, nitrogen oxides can serve as a temporary sink for the ozone depleting chlorine monoxide (ClO), so the net effect is uncertain. NO_x also is a precursor to acid deposition.

Carbon Dioxide (CO_2).

The concentration of CO_2 has been increasing in recent years by an average of about 0.5% annually. Carbon dioxide links the issue of stratospheric ozone depletion to that of the global climate change issue primarily because of its role as a greenhouse gas. As such, it will absorb solar radiation being radiated from the surface of the earth and re-radiate it in all directions, thus increasing the global warming. Because it is a greenhouse gas, CO_2 modifies the temperature structure of the atmosphere, cooling the stratosphere. Less ozone is destroyed if the stratosphere is cooler, so the effect of CO_2 acting alone is to decrease ozone depletion in the stratosphere.

Methane (CH_4).

Methane has been increasing fairly constantly at a rate of about 1% annually. Resulting from both natural and man-made processes, methane is involved in several important reactions in the atmosphere. Through its effect on the amounts of water vapor in the stratosphere methane can lead to destruction of stratospheric ozone. Water droplets may act as a surface upon which the reactions that destroy ozone occur. The increase or decrease of ozone depletion will depend upon where the water vapor is produced. Ozone depletion will increase if water vapor increases in the stratosphere. But an increase in water vapor in the troposphere will heighten the greenhouse effect--water

vapor is the most important greenhouse gas--and decrease ozone depletion through cooling the stratosphere.

A further effect of methane occurs in the troposphere. Here, when methane is oxidized, it produces an increase in the amount of tropospheric ozone. This reaction occurs in the presence of nitrogen oxide.

Natural sources of methane include natural wetlands, arctic tundra, agricultural crops such as rice paddies, and ruminate animals. Man-made sources of CH_4 include the production of fossil fuels such as natural gas and oil, and cement production. Although our understanding of the global methane budget, the relationship between sources, transformations and sinks worldwide, is still limited, it is estimated that natural processes contribute about half of the total methane production.

Carbon Monoxide (CO).

Carbon monoxide is not a radiatively important trace gas, but it is involved indirectly in both stratospheric ozone destruction and global warming. Carbon monoxide controls the concentration of the hydroxyl radical (OH) in the troposphere, which has a direct effect on the concentration of methane. The concentration of methane, as described earlier, plays a role in the amount of tropospheric ozone as well as stratospheric ozone. Methane is also a very important contributor to the greenhouse effect. Although calculations are highly variable, estimates indicate that the concentration of carbon monoxide is increasing at about 1% per year.

Stratospheric and Tropospheric Ozone (O_3).

Scenarios currently in widespread use suggest that the stratospheric component of the total ozone column will decrease over time, whereas the tropospheric constituents of the total ozone column will increase. Whether or not there will be an overall increase in the level of ultraviolet radiation reaching the surface of the earth is still uncertain. Even if the levels of ultraviolet radiation at the earth's surface were not to change, the photochemical reactions involving ultraviolet radiation and the interaction of ozone with various other atmospheric gases would alter the distribution of ozone in the atmospheric column. Changes in the concentration and altitude of ozone will play a major role in altering temperature and atmospheric processes affecting current climate and perhaps add to long-term global climate change.

Increased levels of ultraviolet radiation reaching the earth's surface also will increase the production of ozone at ground level through photochemical reactions. These conditions affect regional air quality. Tropospheric ozone formation takes

place in the presence of nitrogen oxide. In addition, hydrogen peroxide (H_2O_2) is produced. H_2O_2 is a strong oxidant and a catalyst in the production of sulfuric acid from sulfur dioxide. These two processes illustrate the linkage between stratospheric ozone depletion and acid deposition. Sulfur dioxide and nitrogen oxides are the two major precursors to acid deposition.

Trace gases affecting ozone also contribute to global climate change. Any efforts by humans to address the potential problems in either area will influence the other. If global warming were to begin, efforts to address the rise in greenhouse gases could increase ozone depletion. Restraints imposed on the buildup of carbon dioxide, methane, and nitrous oxide to control their contribution to global warming, might reduce their role as moderators of potential ozone depletion in high CFC emission scenarios [7].

BIOLOGICAL INTERACTIONS

A major consequence of decreasing the ozone layer is an increase in the transmission of UV-B radiation to the earth's surface. Scientists have identified many potentially serious effects on the environment and on human health from increased exposure to UV-B radiation. These include damage to agricultural crops, forests, marine organisms, materials, as well as human health. Eye disease, immunosuppression, skin cancer and melanoma have been linked to UV-B exposure. Changes associated with an altered global climate, such as increased CO_2 levels, interact with the effects of UV-B radiation.

Terrestrial Ecosystems.

In assessing the impact of increased exposure of crops and terrestrial ecosystems to UV-B radiation it must be recognized that existing knowledge is in many ways deficient. The effects of enhanced levels of UV-B radiation have been studied in species from only a few representatives of the major terrestrial ecosystems. We derive most of our knowledge from studies conducted at mid-latitudes upon agricultural crops. Despite uncertainties resulting from the complexities of field experiments, the data presently available suggest that plant photosynthesis is vulnerable to increased levels of solar UV-B radiation [1]. Unlike drought or other geographically isolated stresses, stratospheric ozone depletion could affect all areas of the world, including ecosystems whose UV-B sensitivity has not been investigated.

In general, UV radiation causes reduced leaf and stem growth, lower total dry weight, and lower photosynthetic activity in sensitive cultivars of plant species [8]. Less photosynthesis decreases the amount of CO_2 fixed by plants and exacerbates the

rise in CO_2 levels. Higher CO_2 may lead to global warming. This illustrates a direct link from an effect of stratospheric ozone depletion through terrestrial ecosystems to climate change.

Increased levels of UV-B radiation also may affect forest productivity. Only limited data are available on coniferous species, but about one-half of the species of seedlings studied were adversely affected by UV-B radiation [9]. Existing data also suggest that increased UV-B radiation will modify the distribution and abundance of plants. Even small changes in competitive balance over a period of time can result in large changes in community structure and composition [10].

Aquatic Ecosystems.

Current evidence indicates that ambient solar UV-B radiation is an important limiting ecological factor in marine ecosystems. Even small increases of UV-B exposure could result in significant ecosystem changes [11]. In marine plant communities, a change in species composition rather than a decrease in net production would be the probable result of enhanced UV-B exposure [12]. A change in community composition at the base of food webs may produce instabilities within ecosystems that likely would affect higher trophic levels [13].

Inhibition of marine microbial activity by increasing UV-B radiation could have important consequences for several global biogeochemical cycles. Phytoplankton photosynthesis in the upper layer of the oceans provides a sink for approximately 80% of the anthropogenic CO_2 released to the atmosphere. Bacterial activity in the oceans provides probably the most important global source of CH_3I and CH_3Cl (the only significant natural source of chlorine to the stratosphere). Microorganisms in aquatic ecosystems produce large quantities of methane and nitrous oxide. Chemical and photochemical oxidation of natural organic matter in water bodies produces carbon monoxide. Enhanced UV-B radiation, resulting from stratospheric ozone depletion, can alter these processes and affect the levels of the various greenhouse gases in the atmosphere. In addition, UV radiation may affect the populations of marine microorganisms that produce dimethyl sulfide, a compound involved in cloud nucleation.

Human Health.

UV-B radiation has many adverse affects on human health. Kripke [14], van der Leun [15], and the U.S. EPA [1] summarize the potential health effects of UV-B radiation. Probably the best defined health effects are increases in skin cancer cases expected to result from even small increases in UV-B radiation reaching the earth's surface. However, skin cancer affects only a small minority of the world's population, light-skinned caucasians, and therefore is not a significant global problem.

Another important health concern -- with potentially more extensive impacts on more diverse human populations than skin cancer -- is the effect of increased UV-B radiation on human immune suppression. Adverse ocular effects have also been documented from enhanced UV-B radiation, including an increase in the incidence of cataracts in exposed populations. A relationship to melanoma incidence is also suspected.

CFCs, as mentioned above, are important greenhouse gases and contribute to global climate change. Several elements of climate change could have important human health effects. Higher temperatures will increase heat stress in humans, especially among the elderly. Increased temperature combined with changes in precipitation distribution could alter the geographic distribution of diseases and parasites. It could, for example, allow the poleward migration of vector borne diseases, and alter the distribution of diseases that are related to human practices. The distribution, for example, of bilharzia, a disease associated with irrigation practices, would change with evolving changes in temperature and rainfall.

STATE OF KNOWLEDGE

Table II illustrates differences in our state of knowledge regarding selected anticipated biological effects and their potential global impact, as viewed by an expert subcommittee of EPA's Science Advisory Board [16]. One of the dilemmas we face is that we know too little about effects that have the greatest potential for widespread global impacts. For example, the current knowledge of potential effects of increased UV-B radiation on the human immune system is relatively low, but the worldwide impact on human health could be quite high.

POLICY INFORMATION NEEDS

Many uncertainties remain regarding the effects of stratospheric ozone depletion and global climate change. With both of these issues, scientists should structure research around questions that are explicitly relevant to policy decisions. Using "policy-relevant questions" as the framework for research provides the rationale for undertaking specific initiatives. The questions that follow are based on fundamental information needs relevant to stratospheric ozone depletion, including a question addressing the information needed about linkages between ozone depletion and climate change (question 4).

1) How widespread are the potential effects of UV-B radiation? What populations, systems or substances are at greatest risk? An increase in UV-B radiation will continue to exert some degree of influence on man and the environment for the

TABLE II. Potential effects of increased UV-B radiation resulting from decreased stratospheric ozone

Effects	State of Knowledge	Potential Global Impact
Plant Life	Low	High
Aquatic Life	Low	High
Melanoma	Low	Moderate
Other Skin Cancer	Moderate to high	Moderate
Immune System	Low	High
Cataracts	Moderate	Low
Climate Impacts*	Moderate	Moderate
Tropospheric Ozone	Moderate	Low**

* Contribution of both stratospheric ozone depletion itself and gases causing such depletion to climate changes.

** Impact could be high in selected areas typified by local or regional scale surface-level ozone pollution problems.

Modified from Kripke [16].

foreseeable future. This stress will transcend regional and national boundaries, exerting significant effects on widely separated ecosystems and populations. These two attributes make understanding the effects of UV-B radiation on biological and human systems of critical importance.

2) How intensive are the effects of UV-B irradiance? What are the doses that would pose a significant risk? The response of systems to UV-B radiation may differ significantly for different life stages of the same species as well as by latitude and season. What are the specific dose-response relationships, and what mechanisms are involved? Identification of basic and common mechanisms of damage will allow extrapolation of dose-response models to other systems not yet studied.

3) If the dose of UV-B radiation is reduced, what is the anticipated rate and extent of recovery of sensitive systems?

Organisms and ecosystems generally (but not always) recover from environmental stress. It is important to know to what degree and at what rate individual organisms and ecosystems can repair the damage inflicted by enhanced UV-B irradiance. In managed ecosystems (agriculture and silvaculture), UV-B tolerant species may replace less tolerant species. In natural ecosystems some species may be able to adapt over time to increasing UV-B irradiance.

4) What interactions occur between increased UV-B radiation, global climate change and atmospheric pollutants? The composition of the atmosphere depends to a large degree on the natural and man-made emissions of greenhouse gases such as carbon dioxide, CFCs, methane, and nitrous oxide. If new data suggested that increasing UV-B radiation would alter biogeochemical cycles involving these chemicals and result in a disruption of ecosystems or change in global climate, additional regulation to protect the stratospheric ozone layer may be necessary.

5) What mitigation options can be applied? To which systems? Chemicals with less ozone-depleting potential can be used as alternative substances, such as for aerosol propellants. But substitutes are not currently available for some ozone-depleting compounds. Recovery and reuse of substances also is a viable option. We also need to develop mitigative responses to the effects of UV-B radiation, including the replacement of sensitive species with more UV-B tolerant species. Options relevant to the human system are more tenuous and are important to investigate.

Both policy makers and scientists should periodically review and revise this list of questions to reflect the current state of science.

CURRENT ACTIVITIES

The depletion of stratospheric ozone and subsequent increase in UV-B radiation is a problem of global proportions, and one that is not occurring in environmental isolation. Other changes are occurring, including global climate change, acid deposition, and other air pollution. Scientists must examine these issues collectively through an integrated research approach.

As of recently, a concerted effort is recently underway in the United States and numerous other countries in response to plans and initiatives under the International Geosphere-Biosphere Program (IGBP). IGBP, which was launched in 1986 by the International Council of Scientific Unions [17], is the first truly international scientific attempt to integrate research on global climate change, stratospheric ozone depletion, and other issues into what has become known as Global Change.

A report by the National Academy of Sciences' Committee on Global Change [18] suggests research strategies to both the U.S. government and the IGBP, and a report of the White House Committee on Earth Sciences [19] describes both scientific research and approach strategies proposed by U.S. federal agencies. Among the research agencies actively involved in development of the U.S. Global Change Research Program are the:

Environmental Protection Agency (EPA)
Department of Agriculture (USDA)
Department of Energy (DOE)
Department of the Interior (DOI)
National Oceanic and Atmospheric Administration (NOAA)
National Science Foundation (NSF)
National Aeronautics and Space Administration (NASA)

Late in 1988, the Intergovernmental Panel on Climate Change (IPCC) was created by the United Nations Environmental Program (UNEP) and the World Meteorological Organization (WMO) to address the issue of climate change. International working groups have already begun to evaluate our knowledge of the underlying science of climate change, its possible impacts, and our possible response strategies. Many of the participants have been intimately involved in the events leading to the Montreal Protocol, and it is expected that the results of the IPCC process will reflect a sensitivity to the linkages between global environmental issues.

Success in addressing the global problems facing us today is dependent upon such international and interagency coordination. Similarly, it is important to address scientifically related global problems in a coherent fashion. We must keep in mind, as we plan our research and policy development both domestically and internationally, that stratospheric ozone depletion, global climate change, and other issues such as acid deposition are intricately and inexorably linked.

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